Novel silicon and polymer sensors in acoustics

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Abstract

Acoustic sensing has witnessed two important innovations in recent years. Firstly, silicon microphones fabricated with the methods of micromachining based on capacitive and optical sensing principles have been developed and are already in commercial use. These transducers show advantages compared to conventional microphones, such as miniaturized size, heat resistance, and insensitivity against vibration. Secondly, piezoelectret sensors, based on a new class of cellular polymers with very high piezoelectric coefficients, are presently being designed and investigated. Microphones, pickups, and vibration sensors of this kind show small harmonic distortion, large sensitivity and low noise level and are of very simple design.

Introduction

Acoustic sensing has been dominated for decades by electret microphones. These transducers, first described in 1962 [1], are condenser microphones with permanently charged dielectric which do not require a dc bias. Electret microphones are of simple design and have good acoustic properties. They are commercially available since 1968 and are nowadays made in quantities of 2 billion annually, accounting for 80 to 90 % of the worldwide microphone market.

In recent years the field of acoustic sensor technology, just as other areas of sensor engineering, has experienced significant innovation. This can be attributed to several developments, such as the advances of silicon technology and the availability of new electroactive materials. Work based on these evolutions has resulted in novel acoustic sensors, for example high-quality silicon condenser microphones, opto-acoustic silicon sensors, and so-called piezoelectret sensors. The foundations of these fields and some of the new acoustic sensors based on these technologies will be briefly discussed in the following.

Silicon microphones

Silicon microphones are made on silicon wafers with the methods of micromachining. These methods are borrowed from microelectronics and consist of lithography-, doping-, deposition-, and etching processes [2]. A large number of microphones with very reproducible properties can be realized on a single wafer, as Fig. 1 shows. A number of transducer principles has been applied in the design of silicon microphones. Among these are the capacitive, piezoelectric, piezoresistive, FET-modulating and opto-acoustic concepts.

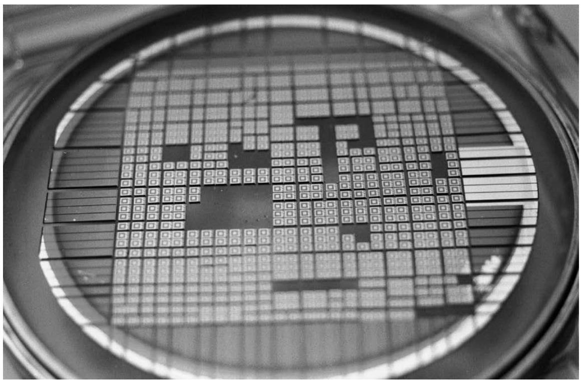

Fig. 1: Processed wafer with large number of silicon microphones.
The chips are already separated and partly removed

Among these, the most successful variety is the capacitive silicon microphone. This relatively simple device consists of a membrane separated by an air gap from a rigid backplate, as shown in Fig. 2. If the system is polarized with a small dc bias, excitation of membrane vibrations by a sound wave generates an electric output signal proportional to the sound pressure.

Such silicon condenser microphones were first proposed in 1983 [3]. They were implemented as two-chip sensors, consisting of a membrane chip and a backplate chip [4,5] and later as single-chip sensors [6,7], such as the microphone shown in Fig. 2. These single-chip sensors are processed with a sacrificial-layer technology where the air gap is obtained by removing an oxide layer originally deposited between membrane and backplate by an etching process. In recent years, several variations of such microphones have been discussed, for example transducers with corrugated membranes which allow for larger membrane excursions [8,9]. The microphone illustrated in Fig. 2 is of this design.

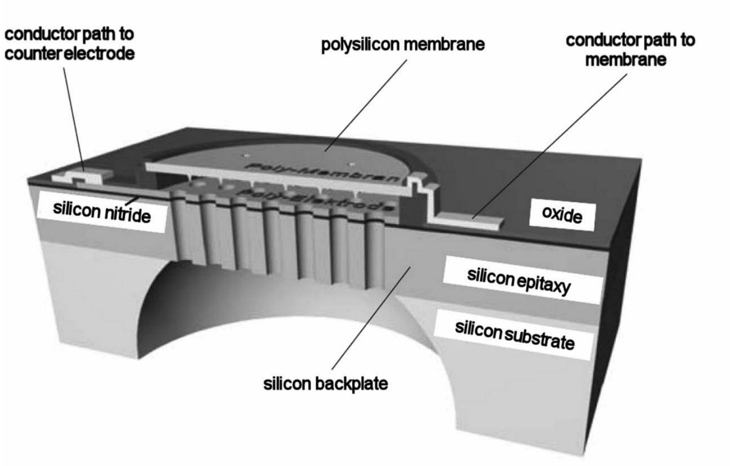

Fig. 2: Single-chip capacitive silicon microphone [9].

Typical silicon condenser microphones have membrane areas of about 1 mm^2, membrane thicknesses of 0.2 to 0.4 µm, air gaps of 1 to 2 µm, resonance frequencies in the near ultrasonic range and sensitivities of approximately 10 mV/Pa. They require bias voltages of only a few Volts and their equivalent noise level is 35 to 40 dB(A). They are furthermore shock resistant and insensitive to vibration since their membranes have a relatively small mass per unit area. Such microphones may be operated permanently at temperatures up to 100°C and up to 260°C for short periods of time. Thus, they can withstand the heat produced during reflow soldering processes and may be used as SMD's on printed circuit boards. Silicon condenser microphones, such as the type shown in Fig. 3, have been commercialized a few years ago [10,11] and are now finding applications in mobile phones, notebooks, PDA's, digital cameras, and MP3-players. They are already made in quantities of 300 million annually.

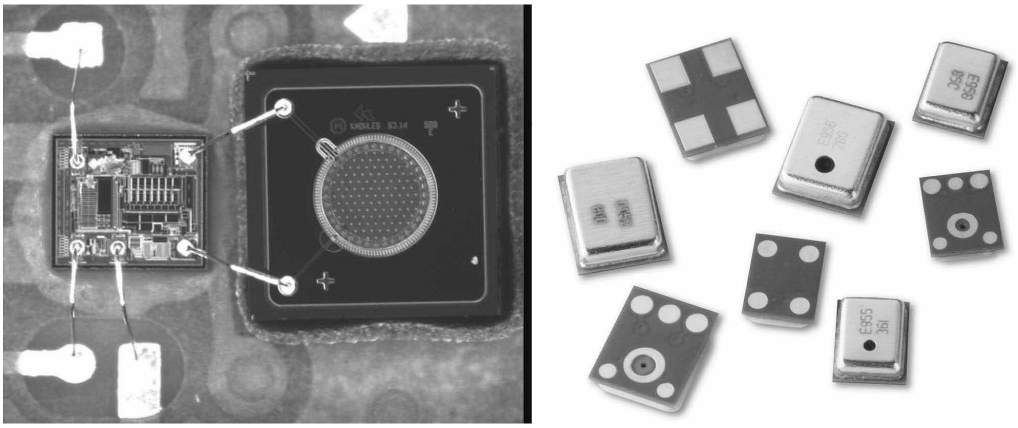

Fig. 3: Commercial silicon condenser microphones: MEMS die and CMOS circuit (left) and fully packaged microphones (right) [11]

Optical microphones based on the silicon technology are also finding recent attention. Several operational principles for these transducers have been described, mostly based on phase or amplitude modulation of laser light by a moving membrane. An implementation of such a microphone is shown in Fig. 4 [12]. It consists of a diaphragm and a diffraction grating back electrode. The grating is illuminated with laser light (e.g. from a vertical cavity surface emitting laser, VCSEL). Part of the light is directly reflected from the grating while another part is transmitted and reflected from the diaphragm. The arrangement constitutes a Michelson interferometer and allows the detection of diaphragm deflections caused by the incident sound.

An important advantage of this sensor compared to the silicon condenser microphone is the absence of squeeze-film damping and the accompanying high displacement-detection resolution. Squeeze-film damping due to air motion between diaphragm and grating is almost completely eliminated because of the relatively large distance of 6 µm between these two components. For a microphone with a diameter of 1.5 mm, a noise level of 24 dB(A) has been determined, which is about 12 dB lower than that of commercial silicon microphones. As can be seen in Fig. 5, the measured frequency response of the deflection compares favorably with the simulated response up to the resonance frequency [12].

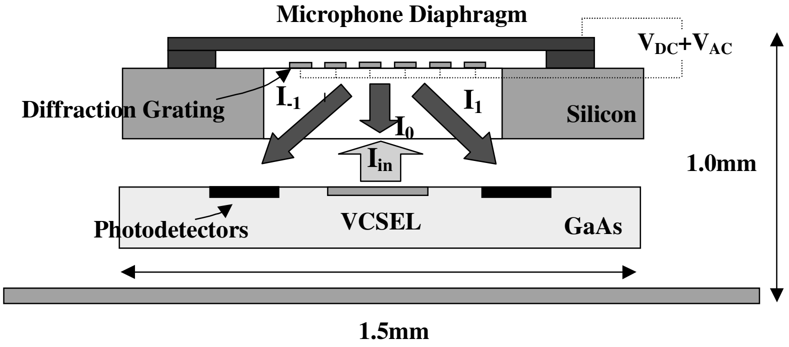

Fig. 4: Optical silicon microphone (upper part) with semiconductor laser and photo detectors(lower part) [12].

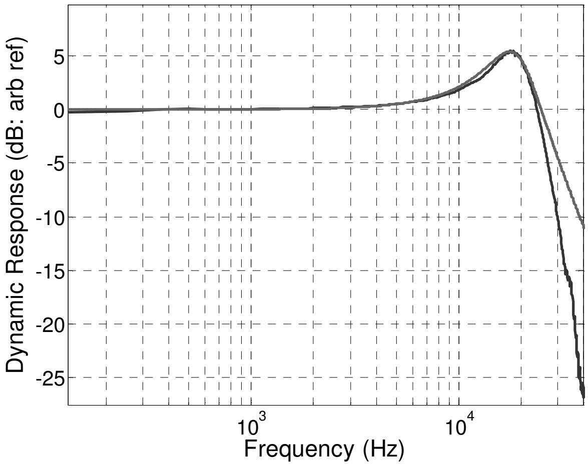

Fig. 5: Frequency response of optical silicon microphone [12]. Upper line: simulated response, lower line: measured response.

Optical microphones with directional characteristics based on the gradient principle have also been described. In one implementation [13], a novel diaphragm design is used in which the diaphragm is not actuated by sound pressure on its two sides, as in a conventional differential microphone. Instead, the pressure gradient causes the membrane to rotate about a pivot placed under the membrane. This reduces the noise level considerably and the principle can even be used to implement second order differential microphones [14].

Piezoelectret microphones

Ferroelectrets (or piezoelectrets) are a new group of piezoelectric polymer foams often consisting of polypropylene (PP) [15-17]. A cross section of such a ferroelectret film is shown in the upper part of Fig. 6. The charge distribution obtained after corona charging is schematically illustrated in the lower part of the Figure. The voids with their positive and negative charges at the air/polymer-interfaces possess large dipole moments which induce image charges in the metal electrodes. Application of an external force changes the dimension of the voids, which in turn changes their dipole moments and the image charges in the electrodes. Therefore, ferroelectrets are piezoelectric. An advantage of ferroelectrets is that their piezoelectric and mechanical properties can be easily adapted to specific applications by pressure expansion processes, which change the thickness and Young's modulus of the films.

Further advantages of ferroelectret films are high piezoelectric d_{33}-coefficients, low weight, high flexibility, mechanical stability, availability in large areas, and low material cost [16].

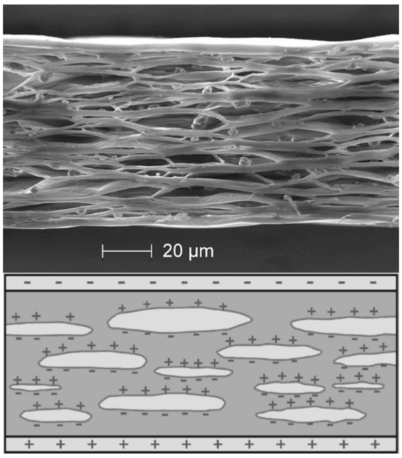

Fig. 6: SEM image of cross section of cellular PP film of 70 µm thickness (top) and schematic view of charge distribution in this material (bottom).

Because of their piezoelectric d_{33}-coefficients, electrical signals are generated when ferroelectret films are exposed to sound waves. The large piezoelectric d_{33}-coefficient allows one to construct high-quality microphones of simple design [18], since an air gap, as in condenser and electret microphones, is not required.

Despite their simplicity, piezoelectret-microphones have very low harmonic distortion, high cut-off frequency and high sensitivity [19]. The high sensitivity is obtained by the use of film stacks, were an electrical series connection of the individual films is realized and the open-circuit sensitivity of the microphones therefore increases proportionally to the number of films.

Since the total capacitance of the film stack decreases inversely proportional to the number of films and since lower microphone capacitance reduces the output signal due to capacitive voltage division at the FET input stage, piezoelectret microphones with coiled film stacks and large stack capacitances are advantageous [19]. Two different types of such microphones are shown in Fig. 7. In the microphone in Fig. 7 (left), the FET is placed beneath the film stack and one side of the stack is clamped and electrically contacted in the center of the cylindrical arrangement. For mechanical and electrical protection, a housing, not shown in the figure, is needed. In contrast, the entire coiled stack of the microphone shown in Fig. 7 (right) is placed and clamped around the FET. The cylindrical film stack, grounded at the outer side, acts as part of the housing and just the top of the cylinder has to be closed by a piece of film or a small cap.

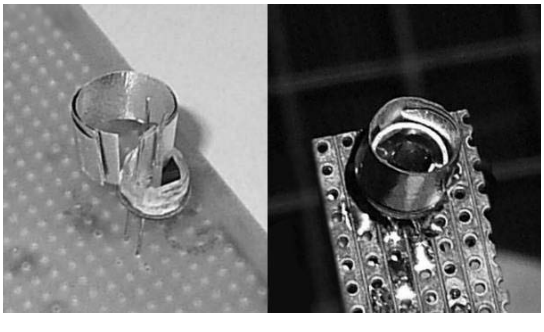

Fig. 7: Two types of piezoelectret microphones with coiled film stacks before mounting the cylindrical housing (left) or the cap (right).

In Fig. 8, frequency responses of the latter microphone type with 4- and 5-films are shown at different stages during their assembly (1) with flat films, (2) with coiled films, and (3) of the completed microphone with mounted cap. Sensitivities up to 14.5 mV/Pa were found and equivalent noise level of about 25 dB(A) were measured for the 5-film microphone.

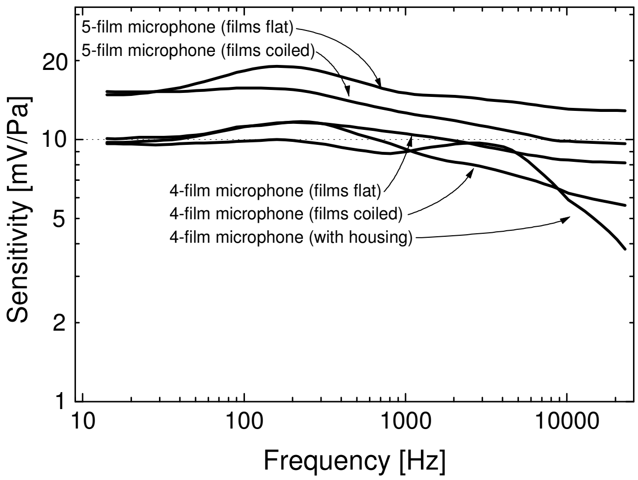

Fig. 8: Free-field responses of 4- and 5- film microphones measured in an anechoic chamber. Responses of microphones with flat film stack, with coiled stack, and with coiled stack and mounted cap are shown.

Recently, omnidirectional and directional microphones were built with ferroelectret films made of layers of the fluoropolymers FEP and PTFE [20-22]. These microphones are more temperature resistant than microphones based on PP films and can be used up to 90°C. Using two such films, placed at a distance of 2.3 cm, and two separate preamplifiers, a gradient microphone (i.e. a differential array) was realized by digitizing and subtracting the two output signals in real time [23]. Directivity measurements performed in an anechoic chamber are shown in Fig. 9. The cardioid characteristic was achieved by time shifting the two signals before subtraction.

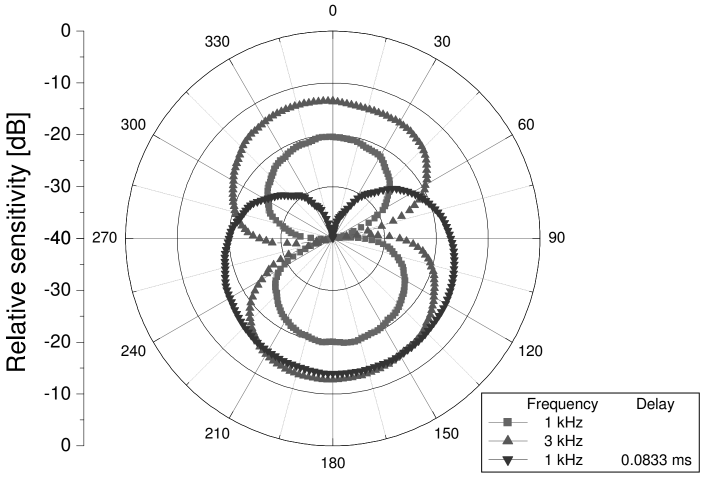

Fig. 9: Directivity of a piezoelectret gradient microphone, with and without time delay between the output signals of the two PTFE/FEP-films, measured at different frequencies [23].

Besides microphones, other applications of these materials in acoustic sensors have been proposed. Among these are pickups for string instruments [24], accelerometers [25], hydrophones [26] and ultrasonic sensors [27]. In view of the specific properties of the ferrolelectret materials, some of these or yet other applications might be of interest in future acoustic sensing devices.

Outlook

During recent years, new applications of acoustic sensors have steadily emerged. Because of the different technical requirements for the diverse applications, devices are needed which satisfy distinct requirements with respect to vibration sensitivity, shock- and temperature resistance, equivalent noise level, frequency range, and price. The specific strengths of the two sensor types discussed above and also of the established technologies allow one to select the best-suited sensors for every application.

Acknowledgments

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